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Parametric analysis for the installation of solar dish technologies in Mediterranean regions

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ABSTRACT

In this work a feasibility study is carried out in order to investigate whether the installation of solar dish technologies for power generation in Mediterranean regions is economically feasible. The study takes into account the available solar potential for a typical Mediterranean country, such as Cyprus, as well as all available data concerning the current renewable energy sources policy of the island, including the relevant feed-in tariff of 0.26€/kWh. In order to identify the least cost feasible option for the installation of the solar dish plant a parametric cost–benefit analysis is carried out by varying the solar dish plant capacity, the solar dish plant capital investment and the CO_2 emissions trading scheme price. The results indicated that the installation of solar dish plants in Mediterranean regions is economically feasible only in some cases, when a feed-in tariff incentive scheme exists, and that the size and the capital cost of the solar dish power plant are critical parameters affecting the economic viability of the technology.

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1. Introduction

Solar thermal power generation utilizes the sun as a source of heat which can be exploited by concentrating that heat and using it to drive a heat engine to produce power. As such, solar thermal power generation is much more closely related to traditional forms of power generation based on fossil-fuel combustion which also rely on heat engines to convert heat into electrical energy. Current solar thermal power technologies are distinguished in the way they concentrate solar radiation, such as (a) parabolic trough systems, (b) solar tower systems and (c) solar dish systems [6].

Solar dish technology is the oldest of the solar technologies with a number of installations and operation of demonstrated solar dish systems between mid 80s and mid 90s. Solar dish systems high efficiency, high power densities, modularity, versatility, hybrid operation and their potential for long term low maintenance operation, continues to interest developers and investors in investing in solar dish technology and thus reducing their capital cost. As a result solar dish systems can provide an economical source of electricity and can become a key source of renewable energy in the coming years.

The purpose of this feasibility study is to investigate whether the installation of solar dish technologies for power generation in Mediterranean regions is economically feasible. The study takes into account the available solar potential of a typical Mediterranean country, such as Cyprus, as well as all available data concerning current renewable energy sources (RES) policy of the island, including the relevant feed-in tariff of 0.26€/kWh. In order to identify the least cost feasible option for the installation of the solar dish plant, a parametric cost–benefit analysis is carried out by varying the following parameters: (a) solar dish plant capacity at 25 MWe or 50 MWe or 100 MWe, (b) solar dish plant capital investment ranging from 2000€/kWe to 8000€/kWe in steps of 1000€/kWe and (c) CO_2 ETS price at 0€/t_{CO_2} or 30€/t_{CO_2}.

In Section 2, the solar dish technology is described and in Section 3, the solar dish system applications, benefits and impacts are discussed. In Section 4, the solar dish system installations are presented and in Section 5, the parametric analysis is carried out and the results are discussed in detail. Finally, the conclusions are summarized in Section 6.

2. Solar dish technology

Solar dish systems convert the thermal energy of solar radiation to mechanical energy and then to electrical energy similar to the way that conventional power plants convert thermal energy from the combustion of a fossil fuel to electricity. Solar dish systems use a mirror array, in the shape of a parabolic dish, to reflect and concentrate incoming direct solar irradiation to a receiver, in order to achieve the temperatures required to efficiently convert heat to work. In order to achieve maximum efficiency, these concentrators are mounted on a structure with two axis tracking system, so that the dish can track the sun. The concentrated solar irradiation is absorbed by the receiver and transferred to an engine. The engine converts the heat to mechanical power by compressing the working fluid and then expanding the fluid through a turbine or with a piston to produce work. The engine is coupled to an electric generator to convert the mechanical power to electric power [9].

Solar dish systems have demonstrated the highest solar to electric conversion net efficiency. For example an efficiency of 31.25% achieved by the company Stirling Energy Systems (SES) on February 12, 2008 [14], compared to around 20% of other solar thermal technologies. Therefore, solar dish systems have the potential to become one of the least cost solar thermal technologies. The modularity of these systems allows them to be deployed individually for remote applications, or by groups for distributed generation applications. These systems can also be hybridized with a fossil fuel to provide dispatchable power, a technology which is in the engineering development stage [13].

2.1. Concentrators for solar dish systems

Solar dish systems utilize concentrating solar collectors that track the sun with a two axis tracker. A reflective surface, metalized glass or plastic, reflects incident solar irradiation to a small region called the focus. The size of the solar concentrator for these systems is determined by the engine. At a nominal maximum direct solar irradiation of 1000 W/m^2, a 25 kWe solar dish Stirling system's concentrator has a diameter of approximately 10 m. Typically dishes are between 5 m and 10 m in diameter and with reflective areas of 40–120 m^2 though dishes with reflective area as large as 400 m^2 have been built. Material limitations are likely to restrict the practical size of dishes though dishes up to 15 m in diameter (700 m^2) have been proposed [5,6,16].

Concentrators use a reflective surface of aluminum or silver, deposited on glass or plastic. The most durable reflective surfaces have been the silver glass mirrors, which are similar to the decorative mirrors used for domestic applications. Low cost reflective polymer films have been attempted to be developed but with limited success. In order to accommodate the required curvatures due to the short focal lengths of the dish concentrators, relatively thin glass mirrors (thickness of approximately 1 mm) are required. In addition, glass with low iron content is desirable to improve reflectance. Depending on the thickness and iron content, silvered solar mirrors have solar reflectance values in the range of 90–94%.

The ideal concentrator has a parabolic shape. Some solar concentrators approximate this shape with multiple, spherically shaped mirrors supported with a truss structure as illustrated in Fig. 1. The concentration ratio of the concentrator, which is determined by the concentrator's optical design and accuracy, is defined as the average solar flux through the receiver aperture divided by the ambient direct normal solar irradiation and is typically over 2000. Intercept fractions, which are defined as the

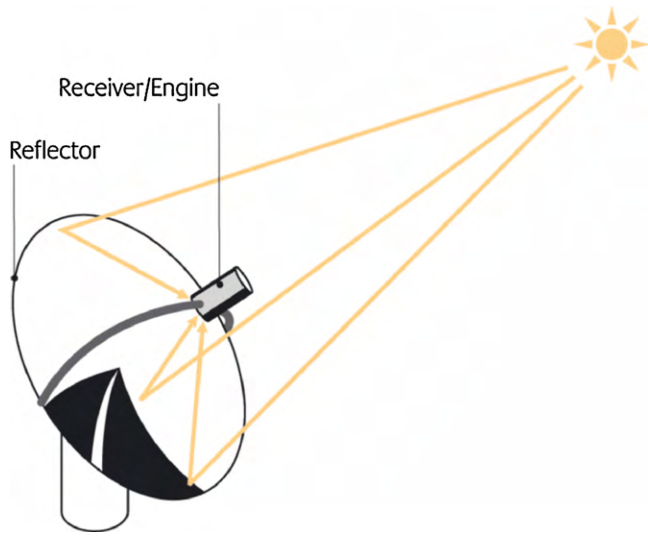

Fig. 1. Solar dish system [6].

fraction of the reflected solar flux that passes through receiver aperture, are typically over 95%.

The two axis tracking system could be an azimuth–elevation tracking or polar tracking. In azimuth–elevation tracking, which is the most common method used in large solar dish systems, the dish rotates in a plane parallel to the earth (azimuth) and in another plane perpendicular to it (elevation), which gives the collector left–right and up–down rotations. Rotational rates vary throughout the day but can be easily calculated. In polar tracking, which is the most common method in small solar dish systems, the collector rotates about an axis parallel to the earth's axis of rotation. The collector rotates at a constant rate of 15°/h to match the rotational speed of the earth. The other axis of rotation, the declination axis, is perpendicular to the polar axis. Movement about this axis occurs slowly and varies by ±23.5° over a year [16].

2.2. Receivers for solar dish systems

The receiver absorbs the energy, which is reflected by the concentrator and transfer it to the engine's working fluid. The absorbing surface is usually placed behind the focus of the concentrator to reduce the flux intensity incident on it. An aperture is placed at the focus to reduce radiation and convention heat losses. Each engine has its own interface issues. Stirling engine receivers must efficiently transfer concentrated solar energy to a high pressure oscillating gas, usually helium or hydrogen, whereas in Brayton receivers the flow is steady, but at relatively low pressures [1].

There are two general types of Stirling receivers, direct illumination receivers and indirect receivers, which use an intermediate heat transfer fluid. Direct illumination receivers adapt the heater tubes of the Stirling engine to absorb the concentrated solar flux and are capable of absorbing high levels of solar flux (approximately 75 W/cm^2) due to the high heat transfer capability of high velocity, high pressure helium or hydrogen. However, balancing the temperatures and heat addition between the cylinders of a multiple cylinder Stirling engine is an integration issue. To solve this issue, liquid-metal, heat-pipe solar receivers are introduced.

In a heat-pipe receiver, liquid sodium metal is vaporized on the absorber surface of the receiver and condensed on the Stirling engine's heater tubes. This results in a uniform temperature on the heater tubes, thereby enabling a higher engine working temperature for a given material and therefore higher engine efficiency. Longer life receivers and engine heater heads are also theoretically possible by the use of a heat-pipe. The heat-pipe receiver isothermally transfers heat by evaporation of sodium on the receiver and condensing it on the heater tubes of the engine. The sodium is passively returned to the absorber by gravity and distributed over the absorber by capillary forces in a wick. Heat-pipe receiver technology has demonstrated significant performance enhancements to an already efficient solar dish Stirling system's power conversion module. Stirling receivers are typically about 90% efficient in transferring energy delivered by the concentrator to the engine [2].

Brayton receiver systems are less developed. In addition, the heat transfer coefficients of relatively low-pressure air along with the need to minimize pressure drops in the receiver make receiver design a challenge. The most successful Brayton receivers have used volumetric absorption in which the concentrated solar radiation passes through a fused silica quartz window and is absorbed by a porous matrix. This approach provides significantly greater heat transfer area than conventional heat exchangers that utilize conduction through a wall. Volumetric Brayton receivers using honeycombs and reticulated open-cell ceramic foam structures have been successfully demonstrated, but for only short term operation. Test time has been limited due to the availability of a Brayton engine. Other designs involving conduction through a wall and the use of fins have also been considered. Brayton receiver efficiency is typically over 80%.

2.3. Engines for solar dish systems

The engine in a solar dish system converts heat to mechanical power in a manner similar to conventional engines that is by compressing a working fluid when it is cold, heating the compressed working fluid and then expanding it through a turbine or with a piston to produce work. The mechanical power is converted to electrical power by an electric generator or alternator. The thermodynamic cycles and working fluids, which have been considered for solar dish systems, are Rankine cycles, using water or an organic working fluid, Brayton, both open and closed cycles and Stirling cycles. Other more exotic thermodynamic cycles and variations on the above cycles have also been considered. The most favorable cycles used by the heat engines are the Stirling and open Brayton cycles. The use of conventional automotive Otto and Diesel engine cycles is not feasible due to the difficulties in integrating them with concentrated solar energy. Heat can also be supplied by a supplemental gas burner to allow operation during cloudy weather and at night. Electrical output in the current solar dish systems prototypes is about 25 kWe for solar dish Stirling systems and about 30 kWe for the solar dish Brayton systems under consideration. Smaller 5–10 kWe solar dish Stirling systems have also been demonstrated.

Stirling cycle engines, used in solar dish Stirling systems, are high temperature, high pressure external heat engines, that use hydrogen or helium working gas. In modern high performance Stirling engines, working gas temperatures of over 700 °C and pressure of 200 bar, are used. In the Stirling cycle, the working gas is alternately heated and cooled by constant temperature and constant volume processes. Stirling engines usually incorporate an efficiency-enhancing regenerator that captures heat during constant volume cooling and replaces it when the gas is heated at constant volume. There are a number of mechanical configurations that implement these constant temperature and constant volume processes. Most of them involve the use of pistons and cylinders. Some use a displacer, which is a piston that displaces the working gas without changing its volume, to shuttle the working gas back and forth from the hot region to the cold region of the engine. For most engine designs, power is extracted kinematically

by a rotating crankshaft. An exception is the free-piston configuration, where the pistons are not constrained by crankshafts or other mechanisms. They bounce back and forth on springs and the power is extracted from the power piston by a linear alternator or pump. The best of the Stirling engines achieve thermal-to-electric conversion efficiencies of about 40%. Stirling engines are a leading candidate for solar dish systems because their external heating makes them adaptable to concentrated solar flux and because of their high efficiency [8].

Currently, the contending Stirling engines for solar dish systems include the SOLO 161 11 kWe kinematic Stirling engine, the Kockums 4-95 25 kWe kinematic Stirling engine, and the Stirling Thermal Motors STM 4-120 25 kWe kinematic Stirling engine. At present, no free-piston Stirling engines are being developed for solar dish applications. All of the kinematic Stirling engines under consideration for solar applications are being built for other applications. Successful commercialization of any of these engines will eliminate a major barrier to the introduction of solar dish technology [16].

The Brayton engine is an internal combustion engine which produces power by the controlled burning of fuel. In the Brayton engine, like in Otto and Diesel cycle engines, air is compressed, fuel is added, and the mixture is burned. In a solar dish Brayton system, solar heat is used to replace (or supplement) the fuel. The resulting hot gas expands rapidly and is used to produce power. In the gas turbine, the burning is continuous and the expanding gas is used to turn a turbine and alternator. As in the Stirling engine, recuperation of waste heat is a key to achieving high efficiency. Therefore, waste heat exhausted from the turbine is used to preheat air from the compressor. The recuperated gas turbine engines, that are candidates for solarization, have pressure ratios of approximately 2.5 and turbine inlet temperatures of about 850 °C. Predicted thermal-to-electric efficiencies of Brayton engines for solar dish Brayton applications are over 30%.

3. Solar dish system applications, benefits and impacts

Solar dish systems have the attributes of high efficiency, versatility, and hybrid operation. The solar dish system can achieve much higher temperatures due to the higher concentration of light. These higher temperatures lead to better conversion to electricity and thus to high efficiency. High-efficiency contributes to high power densities and low cost, compared to other solar technologies. Depending on the system and the site, solar dish systems require approximately 12–16 m^2/kW [16].

However, there are also some disadvantages. Heat to electricity conversion requires moving parts and that results in cost of maintenance. In general, a centralized approach for this conversion is better than the decentralized concept in the dish design. Second, the engine is part of the moving structure, which requires a rigid frame and strong tracking system. Tracking systems tend to be expensive and this means an additional price in the system's overall cost [5].

Because of their versatility and hybrid capability, solar dish systems have a wide range of potential applications. In principle, solar dish systems are capable of providing power ranging from kW to GW. However, it is expected that solar dish systems will have their greatest impact in grid-connected applications in the 1–50 MWe power range. The largest potential market for solar dish systems is large-scale power plants connected to the utility grid. Their ability to be quickly installed, their inherent modularity, and their minimal environmental impact make them a good candidate for new peaking power installations. The output from many modules can be ganged together to form a solar dish farm and produce a collective output of virtually any desired amount. In addition, systems can be added as needed to respond to demand increases. Hours of peak output are often coincident with peak demand. Although, solar dish systems do not currently have a cost-effective energy storage system, their ability to operate with fossil or bio-derived fuels makes them, in principal, fully dispatchable. This capability in conjunction with their modularity and relatively benign environmental impacts suggests that grid support benefits could be a major advantage of these systems.

Solar dish systems can also be used individually as stand-alone systems for applications such as water pumping. While the power rating and modularity of solar dish systems seem ideal for stand-alone applications, there are challenges related to installation and maintenance of these systems in a remote environment. Solar dish systems need to stow when wind speeds exceed a specific condition, usually at about 16 m/s. Reliable sun and wind sensors are therefore required to determine if conditions warrant operation. In addition, to enable operation until the system can become self-sustaining, energy storage (e.g., a battery like those used in a diesel generator set) with its associated cost and reliability issues is needed. Therefore, it is likely that significant entry in stand-alone markets will occur after the technology has had an opportunity to mature in utility and village-power markets. Intermediate scale applications such as small grids (village power) appear to be well suited to solar dish systems. The economies of scale of utilizing multiple units to support a small utility, the ability to add modules as needed, and a hybrid capability make the solar dish systems ideal for small grids.

Because solar dish systems use heat engines, they have an inherent ability to operate on fossil fuels. The use of the same power conversion equipment, including the engine, generator, wiring, switch gear, means that only the addition of a fossil-fuel combustor is required to enable a hybrid capability. For solar dish Brayton systems, addition of a hybrid capability is straightforward. A fossil-fuel combustor capable of providing continuous full-power operation can be provided with minimal expense or complication. The hybrid combustor is downstream of the solar receiver and has virtually no adverse impact on performance. In fact, because the gas turbine engine can operate continuously at its design point, where efficiency is optimum, overall system efficiency is enhanced. System efficiency is expected to be about 30% for a solar dish Brayton system operating in the hybrid mode. For solar dish Stirling systems, on the other hand, addition of a hybrid capability is a challenge. The external, high temperature, isothermal heat addition required for Stirling engines is in many ways easier to integrate with solar heat than it is with the heat of combustion. Geometrical constraints make simultaneous integration even more difficult. System efficiency is expected to be about 33% for a solar dish Stirling system operating in the hybrid mode.

The environmental impacts of solar dish systems are minimal. Stirling engines are known for being quiet, relative to internal combustion gasoline and diesel engines, and even the highly recuperated Brayton engines are reported to be relatively quiet. The biggest source of noise from a solar dish Stirling system is the cooling fan for the radiator. There has not been enough deployment of solar dish systems to realistically assess visual impact. The systems can be high profile, extending as much as 15 m above the ground. However, aesthetically speaking they should not be considered detrimental. Solar dish systems resemble satellite dishes which are generally accepted by the public. Emissions from solar dish systems are also quite low. Other than the potential for spilling small amounts of engine oil or coolant or gearbox grease, these systems produce no effluent when operating with solar energy. Even when operating with a fossil fuel, the steady flow combustion systems used in solar dish Stirling systems and solar dish Brayton systems result in extremely low emission levels. This is, in fact, a requirement for the hybrid vehicle and co-generation

applications for which these engines are primarily being developed.

4. Solar dish installations

Solar dish systems still need further research to overcome non-technical and technical barriers. Solar dish systems require a long-term view in the same way as traditional energy producing plants, and therefore benefit from stable policies and continuity of legal and financial frameworks, ideally favorable for solar dish systems. Additionally, with little commercial experience to draw on, realistic costs estimates for solar dish systems are extremely difficult to make, however, it is expected that cost reduction will result from technical progress. In this section the first pilot installations which are now retired, as well as the plants in operation and under construction around the world are briefly discussed.

4.1. Retired solar dish systems

From the mid 80s until the mid 90s, mainly for demonstration purposes, a number of different solar dish systems ranging in size from 5 kWe to 50 kWe have been built in the USA, Germany, Spain and Japan. The nine most developed systems, whose general characteristics are listed in Table 1 [15], are described below in more detail.

4.1.1. Vanguard 1 system

The 25 kWe Vanguard 1 system was build by Advanco in Southern California in USA, in 1982. The Vanguard solar dish Stirling system used a glass-faceted dish with a diameter 10.5 m, a direct solar irradiation receiver and a United Stirling 4-95 Mark II kinematic Stirling engine. During the 18-month operation of the system, two engine overhauls were required for two different reasons. The first overhaul was required due to the failure of a check valve and the second overhaul was because of a failed oil pump shaft. Other problems, such as excessive noise, vibration and repeated failure of circuit boards, seem to have been the result of using non-hardened gears. Also, there were substantial hydrogen leaks in the system necessitating the replacement of approximately 0.1 m^3/h of system operation. In spite of these problems, the system achieved a reported world's record net solar to electric conversion efficiency of 29.4% and operated for almost 2000 h during the 18-month test phase.

4.1.2. Riyadh system

Two 50 kWe solar dish Stirling systems were built, installed and operated in Riyadh in Saudi Arabia in 1984 by Schlaigh-Bergermann und Partner (SBP) of Germany. Thereby, for the first time large concentrators in metal membrane technology were made. The dishes were 17 m diameter, stretched-membrane concentrators, formed by the drawing of a vacuum in the plenum space formed by the dish rim and front and back stainless steel membranes of 0.5 mm thickness. The optical surface of the dish was made by bonding glass tiles to the front membrane. The SBP dishes used direct solar irradiation receivers and the engines were United Stirling 4-275 kinematic Stirling engines that used hydrogen as the working fluid. The units were fully grid independent and were operated continuously until the mid 90s.

4.1.3. MDAC/SES system

In 1985 a solar dish Stirling system of 25 kWe power was built by McDonnell Douglas Aerospace Corporation (MDAC) in California in USA and the rights to the system at first, were sold to the Southern California Edison Company (SCE) and then to Stirling Energy Systems (SES). The MDAC/SES dish was the first solar dish Stirling system designed to be a commercial product. The dish was nominally an 11 m diameter, faceted, glass–metal design with 88 facets. The dish used direct solar irradiation receiver and the engine was United Stirling 4-95 Mark II kinematic Stirling engine. SCE operated the system until 1988 and reported 13,852 h of operation of a single system, 86.5% system availability during the last two months of operation, production of 28 kW net electric power at solar irradiance of 850 W/m^2 and total production in excess of 720 kWh of net electrical power per day on a good solar day.

4.1.4. Phorzheim system

A prototype solar dish Stirling system of 9 kWe power was erected on an exposed position of the State Garden Show site in Phorzheim in Germany by SBP, in 1992. The concentrator, which had 7.5 m diameter, was constructed in the metal membrane technology and polar suspended. It was equipped with an improved version of the Stirling motor, the V-160 kinematic Stirling engine that used helium as the working fluid and manufactured by SOLO Kleinmotoren GmbH. A first simple semi-automatic system control system was also developed. During the exhibition, the unit was operated continuously for half a year.

4.1.5. SAIC/STM system

A second generation solar dish Stirling system of 25 kWe power that utilizes a faceted, stretched-membrane dish, a direct illumination receiver and Stirling Thermal Motors' kinematic Stirling engine was built by Science Applications International Corporation (SAIC) and Stirling Thermal Motors (STM), in 1993. The system produced 21.6 kWe net power at 24% conversion efficiency and 1000 W/m^2 solar conditions. The engine was the STM 4-120 kinematic Stirling engine, which was a four-cylinder, variable stroke, kinematic Stirling engine that used hydrogen as the working fluid, developed by STM. The variable stroke was achieved through the use of a variable swash plate.

Table 1
Retired solar dish systems [15].

Plant name	Location	Manufacturer	Dish area (m^2)	Efficiency (%)	Capacity (kWe)
Vanguard 1	California, USA	Advanco	86.7	23	25
Riyadh	Riyadh, Saudi Arabia	Schlaigh-Bergermann und Patner	227	N/A	2 × 50
MDAC/SES	California, USA	McDonnell Douglas/Stirling Energy Systems	91	23	28
Phorzheim	Phorzheim, Germany	Schlaigh-Bergermann und Patner	44	N/A	9
SAIC/STM	N/A	Science Applications International Corporation/Stirling Thermal Motors	107	18.5	20
CPG 7 kWe	N/A	Cummins Power Generation	44	15	7
CPG 25 kWe	N/A	Cummins Power Generation	145	N/A	25
DISTAL I	Plataforma Solar de Almeria, Spain	Schlaigh-Bergermann und Patner	44	N/A	3 × 9
DISTAL II	Plataforma Solar de Almeria, Spain	Schlaigh-Bergermann und Patner	57	18	3 × 10

4.1.6. CPG 7 kWe system

A solar dish Stirling system of 7 kWe power was built by Cummins Power Generation (CPG) as part of cost-shared project with US Department of Energy (DOE). This system comprised a solar concentrator, a heat-pipe thermal receiver and a free-piston Stirling engine. The solar concentrator utilized a geodesic space frame, a polar axis drive and a 7.2 m diameter, stretched-membrane, polymer mirror facets. The heat-pipe thermal receiver transferred the absorbed solar heat to the engine by evaporating sodium and condensing it on the tubes of the engine heater head. The baseline engine was the Clever Fellow's Innovative Consortium (CFIC) free-piston engine. The CFIC engine was a twin-opposed configuration that offered the potential of simplicity of design, manufacture and maintenance.

4.1.7. CPG 25 kWe system

Through a second DOE cost-shared program, CPG developed a 25 kWe solar dish Stirling system for grid-connected applications. The 25 kWe project started in 1994 and used a new, high performance, solar concentrator design, with a continuous glass surface comprising a number of pie-shaped gores. The dish was designed to provide about 120 kW of thermal power to the receiver. The engine selected for this system was the Aisen Seiki of Japan, kinematic Stirling engine. The Aisen-Seiki engine is a double-acting, in line four-cylinder Stirling engine nominally rated at about 23 kWe. It operated with helium as the working fluid using variable pressure to control the power output. One of the potential advantages to this engine was that it was based on an automotive engine and, therefore, many of the parts were in mass production. The CPG 25 kWe system operated for a short first time in the spring of 1996 using a heat-pipe receiver and produced 22 kWe net power during on-sun operation.

4.1.8. DISTAL I system

In the project DISTAL I, three solar dish Stirling systems of 9 kWe power, were built on the Spanish-German solar test centre Plataforma Solar de Almeria in Spain by SBP, in 1992. The concentrators, which had 7.5 m diameter, were constructed with the metal membrane technology and polar suspended. They were equipped with an improved version of the Stirling motor, the V-160 kinematic Stirling engine that used helium as the working fluid and manufactured by SOLO Kleinmotoren GmbH. A first simple semi-automatic system control system was also developed. The units were used for demonstration and testing and operated for more than 20,000 h until 2000.

4.1.9. DISTAL II system

In the project DISTAL II, three solar dish Stirling systems of 10 kWe power, were built on the Spanish-German solar test centre Plataforma Solar de Almeria in Spain by SBP, in 1997. The concentrators, which had 8.5 m diameter, were constructed in the metal membrane technology, using an innovative laser welding technique. They were equipped with a direct solar irradiation receiver and an improved version of the Stirling motor, the V-160 kinematic Stirling engine that used helium as the working fluid and manufactured by SOLO Kleinmotoren GmbH. The SOLO Stirling engine had a nameplate power rating of 10 kWe at 1500 rpm and a maximum power rating of 15 kWe at 3600 rpm. The engine was configured in the alpha arrangement with separate, single-acting compression and expansion pistons. A first simple semi-automatic system control system was also developed. The units were used for demonstration and testing and operated in co-operation with German Aerospace Center (DLR) for more than 10,000 h until 2003.

4.2. Solar dish systems in operation

Currently there are nine operational solar dish systems around the world. Most of them are in Europe and are based on Eurodish, which is developed by SBP. The technical characteristics of these plants are shown in Table 2 [14,15], and are described in more detail below.

4.2.1. Infinia system

A parabolic solar concentrator of 4.7 m diameter was manufactured by Infinia Corporation and SBP in 2007 and operates in Spain. The system uses a 3 kWe Stirling engine.

4.2.2. Odeillo's Eurodish Country Reference Unit

The Eurodish system of 10 kWe power was installed on the site of the research institute, close to the famous solar furnace of Odeillo in France by SBP, in 2004. The Country Reference System is exposed to the particularly hard operational conditions of a mountain site of 1600 m altitude with very high solar irradiation and extreme frost and snowfall during winter. The concentrator has a diameter 8.5 m and the unit uses the 161 SOLO Stirling engine.

4.2.3. Seville's Eurodish Country Reference Unit

The Country Reference Unit of 10 kWe power was erected at the ESI on the former EXPO site in Seville of Spain by SBP, in 2004. The concentrator has a diameter of 8.5 m and the unit uses the 161 SOLO Stirling engine. It is operated continuously by the ESI and serves on proving on a site with typical meteorological boundary conditions for sola dish Stirling systems.

4.2.4. Eibelstadt's Eurodish Country Reference Unit

The unit of 10 kWe power was built in a representative location in front of the new building of the Krick Publishing Company by SBP, in Eibelstadt near Wuerzburg in Germany, in 2004. The concentrator has a diameter of 8.5 m and the unit uses the 161 SOLO Stirling engine. The system is operated continuously and successfully.

4.2.5. Vellore's Eurodish Country Reference Unit

This Country Reference Unit of 10 kWe power was constructed on the campus of the University of Vellore in South India by SBP

Table 2
Solar dish systems in operation [14,15].

Location	Manufacturer	Dish area (m^2)	Capacity (kWe)
Spain	Infinia Corporation & Schlaigh-Bergermann und Patner	N/A	3
Odeillo, France	Schlaigh-Bergermann und Patner	57	10
Seville, Spain	Schlaigh-Bergermann und Patner	N/A	10
Eibelstadt, Germany	Schlaigh-Bergermann und Patner	57	10
Vellore, India	Schlaigh-Bergermann und Patner	57	10
Milan, Italy	Schlaigh-Bergermann und Patner	57	10
Almeria, Spain	Schlaigh-Bergermann und Patner	57	2×10
Canberra, Australia	Australian National University/Wizard Power Pty	400	150
Plataforma Solar de Almeria, Spain	Sandia National Laboratories/Stirling Energy Systems	N/A	150

Table 3
Solar dish systems under construction [10,12,17].

Plant name	Location	Manufacturer	Capacity (MWe)
SES Solar One	Mojave Desert, California, USA	Stirling Energy Systems	850
SES Solar Two	Imperial Valley, California, USA	Stirling Energy Systems	750
Big Dish Eraring Power Station	Sydney, Australia	Australian National University/Wizard Power Pty	2.7
Maricopa Solar LLC	Peoria, Arizona, USA	Stirling Energy Systems	1.5
SunCal 2000	Huntingdon Beach, California, USA	Stirling Energy Systems	0.4
Aznalcollar TH	Sanlucar la Mayor, Spain	Abengoa Solar New Technologies	0.08

under participation of local companies, in 2002. The concentrator has a diameter of 8.5 m and the unit uses the 161 SOLO Stirling engine. The unit is in test operation.

4.2.6. Milan's Eurodish Country Reference Unit

This Country Reference Unit of 10 kWe power was installed on the CESI site by SBP in Milan in Italy, in 2002. The concentrator has a diameter of 8.5 m and the unit uses the 161 SOLO Stirling engine. The unit is operated continuously since then.

4.2.7. Almeira's Eurodish testing carrier

The two Eurodish systems of 10 kWe power each on the Spanish-German solar test centre Plataforma Solar de Almeria in Spain were constructed by SBP in 2000. These systems are the first ones with a novel composite concentrator from fibre glass reinforced plastic and a diameter of 8.5 m. The systems are specified by a further improved 161 SOLO Stirling engine and a technical mature drive and control system. Amongst others, the units are used for testing new and improved components and operated in co-operation with DLR.

4.2.8. ANU's Big Dish

The first 400 m^2 pilot experimental Big Dish project of 150 kWe power is under scientific testing at the Australian National University (ANU) since 1994. It is designed for power generation using a 50 kWe steam engine generator or for co-generation applications by solar steam production. Wizard Power Pty Ltd. was established in 2005 to take the Big Dish technology to commercial deployment.

4.2.9. Sandia National Laboratories system

In Albuquerque of New Mexico in USA, the Sandia National Laboratories in co-operation with SES built a six solar dish mini power plant producing up to 150 kWe during the day, in 2005. Each unit consists of 82 smaller mirrors formed in the shape of a dish. The frame is steel, while the mirrors are laminated onto a honeycomb aluminum structure. The engine is a SunCatcher dish engine produced by SES [14].

4.3. Solar dish systems under construction

In the coming years, large-scale solar dish systems are planned to be constructed as illustrated in Table 3 [10,12,16]. Below, the most important projects are described.

4.3.1. SES Solar One

The proposed SES Solar One project in Mojave Desert, California in USA would be a nominal 850 MWe Stirling engine project, with construction planned to begin in late 2010. The primary equipment for the generating facility would include the approximately 34,000, 25 kWe SunCatcher solar dishes, their associated equipment and systems, and their support infrastructure. Each SunCatcher consists of a solar receiver heat exchanger and a closed-cycle, high-efficiency solar Stirling Engine specifically designed to convert solar power to rotary power then driving an electrical generator to produce grid-quality electricity. The proposed project will be constructed on an approximate 40 m^2/kW [11].

4.3.2. SES Solar Two

The proposed SES Solar Two project in Imperial Valley, California in USA would be a nominal 750 MWe Stirling engine project, with construction planned to begin either late 2009 or early 2010. The primary equipment for the generating facility would include the approximately 30,000, 25 kWe SunCatcher solar dishes, their associated equipment and systems, and their support infrastructure. Each SunCatcher consists of a solar receiver heat exchanger and a closed-cycle, high-efficiency solar Stirling Engine specifically designed to convert solar power to rotary power then driving an electrical generator to produce grid-quality electricity. The proposed project will be constructed on an approximate 35 m^2/kW. The project will be constructed in two phases. Phase I of the project will consist of up to 12,000 SunCatchers configured in 200 1.5 MWe solar groups of 60 SunCatchers per group and have a net nominal generating capacity of 300 MW. Phase II will add approximately 18,000 SunCatchers, expanding the project to a total of approximately 30,000 SunCatchers configured in 500 1.5 MWe solar groups with a total net generating capacity of 750 MWe [12].

4.3.3. Maricopa Solar LLC

Tessera Solar and SRP will build a 1.5 MWe solar dish project, Maricopa Solar LLC, in Peoria, Arizona, located in the West Valley of the greater Phoenix area in USA. Maricopa Solar will be the first commercial-scale solar facility built using the innovative SunCatcher concentrating solar–thermal technology, manufactured by SES. The project will consist of 60 SunCatcher dishes. It is expected to be completed in January 2010 [17].

5. Parametric cost–benefit analysis

The main objective of this feasibility study is to investigate whether the installation of solar dish technologies for power generation in Mediterranean regions is economically feasible. The study takes into account the available solar potential of a typical Mediterranean country, such as Cyprus, as well as all available data concerning current RES policy of the island, including the relevant feed-in tariff of 0.26€/kWh. Details concerning Cyprus power system can be found in [7].

5.1. Input data and assumptions

In order to identify the least cost feasible option for the installation of the solar dish plant a parametric cost–benefit analysis is carried out by varying (a) the solar dish plant capacity at 25 MWe or 50 MWe or 100 MWe, (b) the solar dish plant capital investment from 2000€/kWe to 8000€/kWe in steps of 1000€/kWe and (c) the CO_2 ETS price at 0€/t_{CO_2} or 30€/t_{CO_2}. For all above cases the electricity unit cost (or benefit) before tax (in €/kWh), as well as after tax cash flow, net present value (NPV), internal rate of return (IRR) and payback period are calculated. The input data and assumptions used for the above analysis are tabulated in Table 4 and are explained in detail below.

Table 4
Parametric cost–benefit analysis data and assumptions.

Parameter	Value
Technical data	
Plant capacity	25 MW or 50 MW or 100 MW
Annual solar potential	2500 kWh/m^2
Solar thermal collector system	Solar dish
Capital data	
Specific capital cost	2000–8000€/kW
Emissions data	
CO_2 indicator	800 g/kWh
CO_2 ETS price	0€/t_{CO_2} or 30€/t_{CO_2}
Operation and maintenance data	
Annual staff and overheads cost	2,000,000€/year
Annual maintenance cost	1% of capital cost
Other data	
Discount rate	6%
Available feed-in tariff	0.26€/kWh
Economic life of solar thermal plant	20 years
Annual income tax rate	10%

Cyprus lies in the Mediterranean sunny belt with an average yearly solar potential on a flat surface to be around 1790 kWh/m^2. During the months of March and September there is a considerable high sunlight radiation. This provides the fundamental grounds for the adoption of solar thermal technology for generating electricity [5]. For Mediterranean conditions, in the case of using solar dish technology for power generation the annual solar potential is estimated at 2500 kWh/m^2 (two axis tracking potential). The solar dish system used for the purposes of this analysis constitutes by a collector with a projected mirror area of 87.7 m^2, a receiver with an aperture area of 0.184 m^2 and a Stirling Engine of capacity 25 kW.

Solar dish plants for power generation applications are not currently cost-competitive due to the high initial cost. Thus the effect of the capital cost is examined in this parametric analysis by varying the initial expenditure from 2000€/kWe, in steps of 1000€/kWe, up to 8000€/kWe. The capital expenditure may include, among others, the land leasing, the solar dish system, the development and design study, the license fees, the engineering works, the road construction, the connection transmission line, the substation, the commissioning and training, etc.

To estimate the greenhouse gas emission reduction (mitigation) potential of the solar dish power plant, the CO_2 environmental indicator which currently characterizes Cyprus power system of 800 g/kWh is used. In order to take into account the EU ETS system as well as the emerging rules from the Kyoto Protocol, associated with CDM and JI projects, CO_2 ETS prices of 0€/t_{CO_2} and 30€/t_{CO_2} are used. By doing this the number of CO_2 credits (either EURs or CERs or EUAs) that accrue to the solar dish power plant can be determined and their benefit to the cash flow can be calculated.

For the operation cost a fixed annual expenditure of €2,000,000 is taken into account for staff salary and overheads (such as insurance charges). Annual maintenance expenditure is assumed as 1% of the total investment cost. A feed-in tariff of 0.26€/kWh is assumed which is based on the Cyprus Government Grant Schemes for solar thermal power plants. Also, the economic life of the plant is assumed at 20 years which is based on the Cyprus Government Grant Schemes purchase contract period of 20 years. Throughout the simulations, a typical discount rate of 6% is assumed. In order to calculate the after tax cash flows and after tax financial indicators a single 10% income tax rate is assumed that is constant throughout the project life and applied to net income.

5.2. Simulation procedure

In order to identify the least cost feasible options for the installation of a solar dish plant based on the current market regulations (i.e., 20 years purchase contract and a feed-in tariff of 0.26€/kWh) 42 simulations have been carried out based on the data and assumptions discussed in the previous section. For all simulations, the IPP algorithm version 2.1 (independent power producer technology selection algorithm) software tool is employed [3,4].

The software, allows the user to input various technical, financial and environmental parameters of a solar dish plant, such as annual power generation, plant capacity, capital cost, discount rates. Then the operation of the plant is simulated and the key financial feasibility indicators, such as IRR, payback period, NPV are calculated based on the following algorithm: (a) calculate solar radiation in plane of the solar dish, (b) calculate electrical energy delivered by solar thermal plant, (c) calculate system losses, (d) calculate electrical energy delivered to the grid, (e) calculate feed-in tariff benefit, (e) calculate CO_2 emissions avoided benefit and (f) calculate financial feasibility indicators assuming that the initial investment year is year 0, the costs and credits are given in year 0 terms, thus any inflation rate (or the escalation rate) is applied from year 1 onwards and the timing of cash flows occurs at the end of the year.

During the simulations procedure the following financial feasibility indicators are calculated: (a) electricity unit cost or benefit before tax (in €/kWh), (b) after tax cash flow (in €), (c) after tax NPV (is the value of all future cash flows, discounted at the discount rate, in today's currency), (d) after tax IRR (is the discount rate that causes the NPV of the project to be zero and is calculated using the after tax cash flows. Note that the IRR is undefined in certain cases, notably if the project yields immediate positive cash flow in year zero), (e) after tax payback period (the number of years it takes for the cash flow, excluding debt payments, to equal the total investment which is equal to the sum of the debt and equity).

5.3. Results and discussion

In this feasibility study the economic viability for the installation of a solar dish power plant in Mediterranean regions was investigated. The available solar potential of a typical Mediterranean region, such as Cyprus, as well as all available data concerning the RES policy of the island including the relevant feed-in tariff were taken into account. In order to identify the least cost feasible options for the installation of a solar dish plant, a parametric cost–benefit analysis was carried out by varying several parameters. For all simulated cases the electricity unit cost (or benefit) before tax (in €/kWh), as well after tax cash flow, net present value (NPV), internal rate of return (IRR) and payback period were calculated.

The electricity production from a solar dish power plant depends on the available solar potential as well as on the plant efficiency, which includes the operational availability, the losses and the annual degradation of the power plant. The results obtained concerning the annual electricity generation from the 3 sizes of solar dish plants are presented in Fig. 2 and Table 5. For the case of solar dish plant of capacity 25 MW the annual power generation is 32,560 MWh with a capacity factor of 14.87%, whereas for the case of a solar dish plant with a capacity of 50 MWe the annual power generation is 65,438 MWh with a capacity factor of 14.94% and for the case of solar dish plant of capacity 100 MW, the annual power generation is 131,193 MWh with a capacity factor of 14.98%. It is evident that as the size of the solar dish plant increases the electricity production increases as well.

The solar field of the 25 MWe solar dish power plant consists of 20 series with 50 collectors in each series, whereas for the 50 MWe it consists of 40 series with 50 collectors in each series and for the 100 MWe it consists of 80 series with 50 collectors in each series. For all 3 sizes of solar dish plants the distance between each collector is 16 m and between each series is 16 m also. Furthermore,

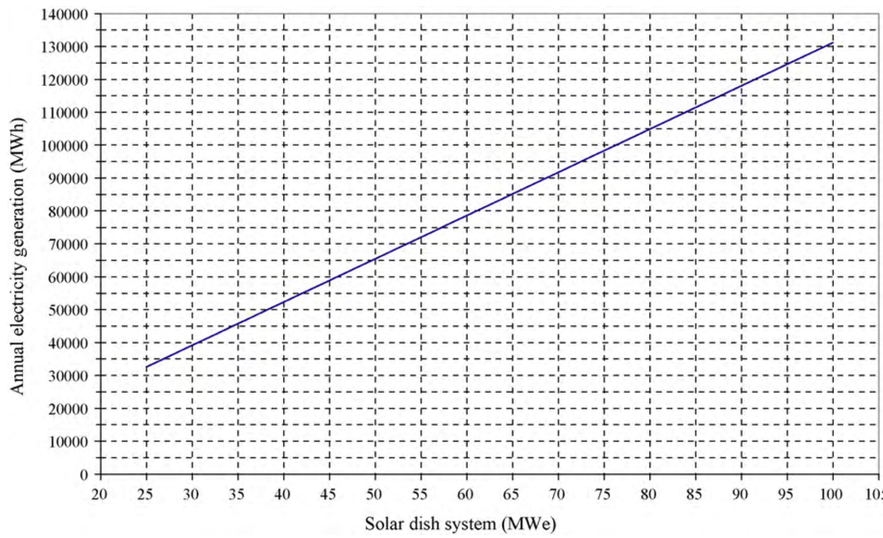

Fig. 2. Results for annual electricity generation from various solar dish plant sizes.

Table 5
Technical and environmental results.

Parameter	Unit	25 MW solar dish plant	50 MW solar dish plant	100 MW solar dish plant
Annual power generation	MWh	32560.34	65437.97	131193.28
Capacity factor	%	14.87	14.94	14.98
Annual CO_2 avoided emissions	t_{CO_2}	26,048	52,350	104,955
Annual barrels of crude oil not consumed	bbl	54,081	108,689	217,905

a distance of 8 m at each side of the field is used for fencing and plant facilities. The total land area required (including shading and other-purpose spaces) for the installation of solar dish plants of various plant sizes is presented in Fig. 3. We observe that as the size of the solar dish plant increases the required land area increases as well. For example in the case of a solar dish power plant with a capacity of 25 MWe the required land area required is approximately 256,000 m^2. Whereas in the case of a solar dish plant with a capacity of 50 MWe, the required land area required is approximately 512,000 m^2 and for the case of 100 MWe solar dish plant, the required land area is approximately 1,024,000 m^2.

The results obtained concerning the annual avoided CO_2 emissions and the annual barrels of crude oil not consumed from the 3 sizes of solar dish plants examined are tabulated in Table 5 and illustrated in Figs. 4 and 5, respectively.

The results obtained concerning the electricity unit cost (or benefit) before tax, for different solar dish plant sizes, are illustrated in Fig. 6. Positive values of electricity unit cost indicate benefit (i.e., profit) whereas negative values indicate cost (i.e., loss). For example, concerning a 25 MWe solar dish power plant and no trading of the avoided CO_2 emissions, in the case of capital cost of 2000€/kWe, the calculated electricity production cost is 21.07€c/kWh. Thus, taking into account a feed-in tariff of 26€c/kWh, the electricity unit benefit before tax is 4.93€c/kWh (positive sign indicating benefit) meaning that for every kWh produced by the solar dish power plant and delivered to the grid a profit (or benefit)

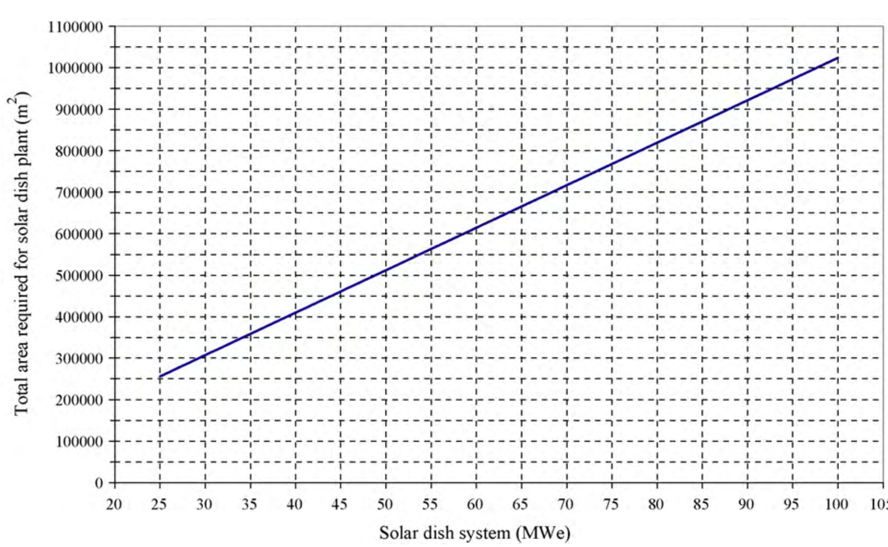

Fig. 3. Results for required area from various solar dish plant sizes.

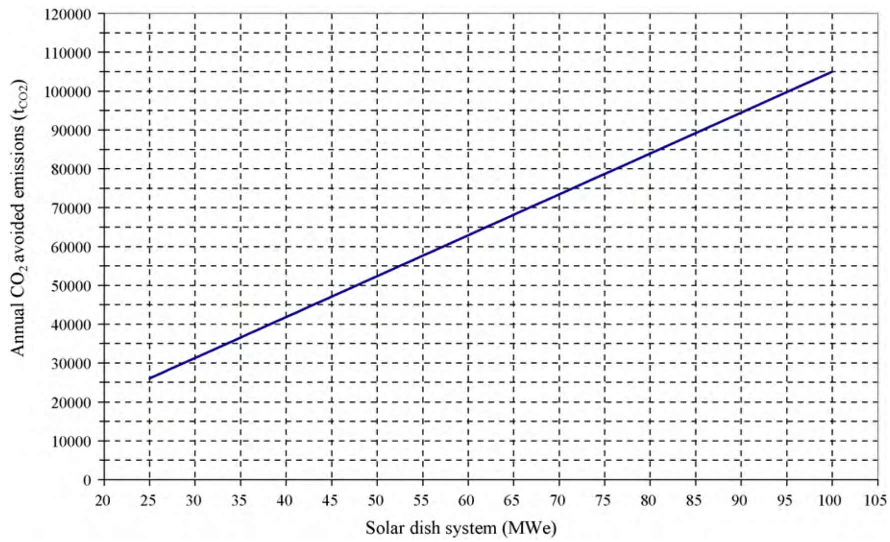

Fig. 4. Results for annual CO_2 avoided emissions from various solar dish plant sizes.

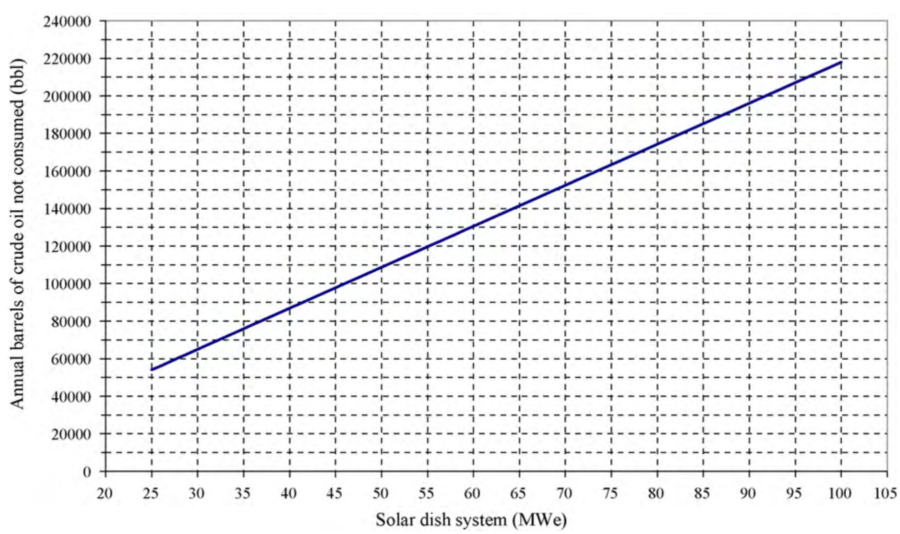

Fig. 5. Results for annual barrels of crude oil not consumed from various solar dish plant sizes.

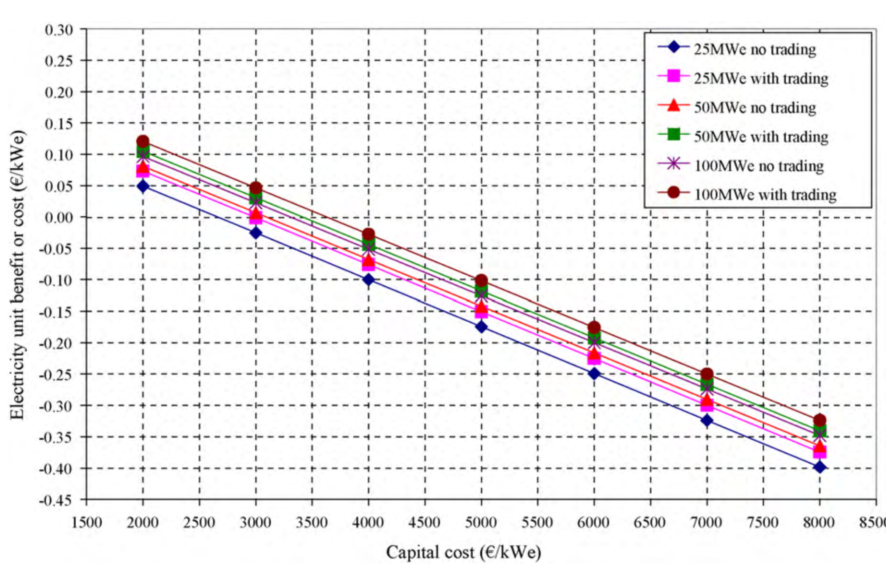

Fig. 6. Before tax electricity unit cost from various solar dish plant sizes with and without CO_2 trading.

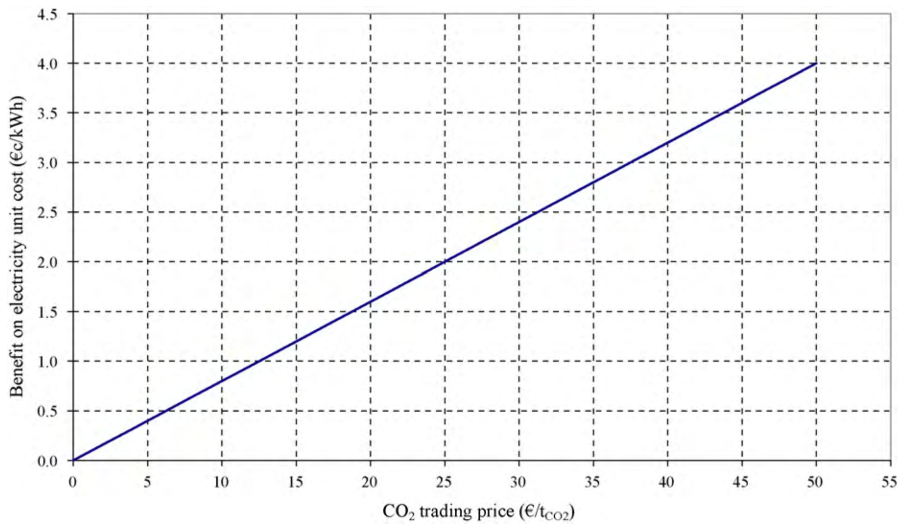

Fig. 7. Benefit of CO_2 trading on solar dish electricity unit cost for various ETS prices.

before tax of 4.93€c will occur. Whereas, in the case of capital cost of 4000€/kWe, the calculated electricity production cost is 35.99€c/kWh. Thus, taking into account a feed-in tariff of 26€c/kWh, before tax electricity unit cost is −9.99€c/kWh (negative sign indicating cost) meaning that for every kWh produced by the solar dish power plant and delivered to the grid a loss (or cost) before tax of 9.99€c will occur.

The results concerning a 25 MWe solar dish power plant in the case of trading the avoided CO_2 emissions at 30€/t_{CO_2} are also illustrated in Fig. 6. For the case of capital cost of 2000€/kWe, the calculated electricity production cost is 21.07€c/kWh. Thus, taking into account a feed-in tariff of 26€c/kWh and the CO_2 emissions trading price of 30€/t_{CO_2}, before tax electricity unit benefit is 7.33€c/kWh (positive sign indicating benefit) meaning that for every kWh produced by the solar dish power plant and delivered to the grid a profit (or benefit) before tax of 7.33€c will occur. Whereas, in the case of capital cost of 4000€/kWe, the calculated electricity production cost is 35.99€c/kWh. Thus, taking into account a feed-in tariff of 26€c/kWh and the CO_2 emissions trading price of 30€/t_{CO_2}, before tax electricity unit cost is −7.59€c/kWh (negative sign indicating cost) meaning that for every kWh produced by the solar dish power plant and delivered to the grid a loss (or cost) before tax of 7.59€c will occur.

It should be mentioned that the additional benefit due to CO_2 emissions trading price of 30€/t_{CO_2} for all cases examined during the simulations performed is calculated at 2.4€c/kWh, as shown in Fig. 7. Finally, the size of the solar dish plant is critical for the viability of the investment. From the simulations performed it is clear that by increasing the size of the solar dish power plant (i.e., from 25 MWe to 50 MWe or 100 MWe) the investment becomes more attractive. This is illustrated in Fig. 6.

The NPV and the payback period are directly related to the cash flow of the investment, and thus, on the electricity unit benefit or cost. Therefore, the results obtained during the simulations concerning after tax NPV and payback period provide similar observations as those discussed in the previous section. The after tax payback period is shown in Fig. 8 where, for the case of the 25 MWe solar dish power plant and no trading of the avoided CO_2 emissions and of capital cost of 4000€/kWe the payback period is approximately 20 years. Whereas in the case of trading the avoided CO_2 emissions at 30€/t_{CO_2} the payback period is approximately 18 years. For the case of the 100 MWe solar dish power plant of capital

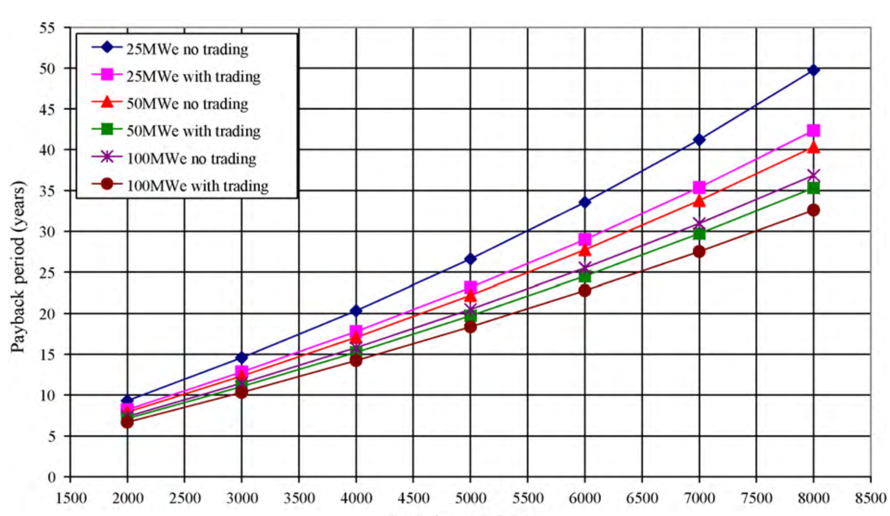

Fig. 8. After tax payback period for various solar dish plant sizes with and without CO_2 trading.

cost 4000€/kWe and trading the avoided CO_2 emissions at 30€/t_{CO_2} the payback period is approximately14 years.

Clearly the installation of solar dish plants in Cyprus is economically feasible only in some cases due to the existence of the current feed-in tariff incentive scheme. Moreover, it is obvious from the above analysis that (a) the size and (b) the capital cost of the solar dish power plant are critical parameters affecting the economic viability of the project. Therefore, solar dish power plants of 50 MWe or 100 MWe are economically more viable than a 25 MWe plant. Regarding the capital cost, plants with capital costs lower than 3000€/kWe are shown to be economically viable in the presence of feed-in tariff in a sense that their after tax payback periods are less than 15 years. Finally, the potential of trading the CO_2 avoided emissions at a trading price of 30€/t_{CO_2} provides an additional economic benefit of 2.4€c/kWh to all solar dish power plants.

6. Conclusions

In this work a feasibility study was carried out in order to investigate whether the installation of solar dish technologies for power generation in Mediterranean regions is economically feasible. The study took into account the available solar potential for a typical Mediterranean country, such as Cyprus, as well as all available data concerning the current renewable energy sources policy of the island, including the relevant feed-in tariff of 0.26€/kWh. In order to identify the least cost feasible option for the installation of the solar dish plant a parametric cost–benefit analysis was carried out by varying the solar dish plant capacity, the solar dish plant capital investment and the CO_2 emissions trading scheme price. The results indicated that the installation of solar dish plants in Mediterranean regions is economically feasible only in some cases, when a feed-in tariff incentive scheme exists, and that the size and the capital cost of the solar dish power plant are critical parameters affecting the economic viability of the technology.

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